

# Generation and control of sound bullets with a nonlinear acoustic lens

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Communicated by L B Freund, Brown University, Providence, RI, February 12, 2010 (received for review October 4, 2009)

Acoustic lenses are employed in a variety of applications, from biomedical imaging and surgery to defense systems and damage detection in materials. Focused acoustic signals, for example, enable ultrasonic transducers to image the interior of the human body. Currently however the performance of acoustic devices is limited by their linear operational envelope, which implies relatively inaccurate focusing and low focal power. Here we show a dramatic focusing effect and the generation of compact acoustic pulses (sound bullets) in solid and fluid media, with energies orders of magnitude greater than previously achievable. This focusing is made possible by a tunable, nonlinear acoustic lens, which consists of ordered arrays of granular chains. The amplitude, size, and location of the sound bullets can be controlled by varying the static precompression of the chains. Theory and numerical simulations demonstrate the focusing effect, and photoelasticity experiments corroborate it. Our nonlinear lens permits a qualitatively new way of generating high-energy acoustic pulses, which may improve imaging capabilities through increased accuracy and signal-to-noise ratios and may lead to more effective noninvasive scalpels, for example, for cancer treatment.

acoustic focusing | nonlinear dynamics | solitary waves | sonic imaging | granular crystals

Acoustic fields enable noninvasive inspection of condensed matter, detection and even thermal excitation via energy focusing. Biomedical imaging (1, 2), detection of underwater objects (3) or damage in materials (4), and hyperthermia surgery via noninvasive scalpels (5–7) stand as prominent examples. The focusing of acoustic waves at a desired location is usually realized with electromechanical transducers and methods such as geometric focusing (4), time-reversal focusing (8), or beamforming via phase lags (5, 9, 10). In geometric focusing, the transducers' geometry is exploited to focus signals. In time-reversal and beamforming methods, appropriate phase delays among acoustic signals are used to focus them in a desired region. Each method is limited by its reliance on actuators, which are incapable of generating compact, nonoscillatory, and high-amplitude signals, typically resulting in cumbersome and application-specific devices. Recently, acoustic metamaterials (11) as well as superlenses (12) and hyperlenses (13) aimed at improving spatial resolution have been introduced. However, their continued reliance on linear wave dynamics limits their spatial accuracy, energy intensity, and dynamic focus control.

Here we introduce an acoustic lens that uses nonlinear wave dynamics to accurately focus high-amplitude acoustic signals, achieving a transient focal region of higher energy density than previously possible. The position, amplitude, and frequency content of the focal region in an adjacent solid or fluid host medium are dynamically controllable. The acoustic lens consists of an array of nonlinear transducers based on discrete power-law materials (e.g., chains of spherical particles) (Fig. 1A). In contrast to linear elastic materials in which force  $F$  and deformation  $\delta$  obey the relation  $F = k_L \delta$ , with stiffness constant  $k_L$ , discrete power-law materials do not support tensile forces and feature an unusual behavior described by  $F = k_N \delta^n$ , with stiffness constant  $k_N$  and power-law exponent  $n > 1$ . The nonlinearity

of the force-deformation relation makes discrete power-law materials a host for compact acoustic waves, which are stable and have easily controllable behavior (14–18). We take advantage of these characteristics to modify incoming acoustic waves into compact, high-amplitude pulses within the lens (see insets in Fig. 1A). These pulses can subsequently be focused in an adjacent fluid or solid host medium.

Power-law materials such as arrays of spherical particles can support linear, weakly nonlinear, and highly nonlinear wave dynamics, depending on the initial strain state of the material, which can be controlled by a static precompression force  $F_0$  (Fig. 1B) (14). For incoming signals leading to low particle interaction forces  $F_m$  such that  $F_m \ll F_0$ , the resulting wave field is linear. If  $F_m \approx F_0$ , the wave field is characterized by the classic weakly nonlinear soliton solutions of the Korteweg–De Vries equation (14, 19), whose phase velocity  $V_s$  depends on wavelength and amplitude (20). The weakly nonlinear regime is depicted as the gray shaded area in Fig. 1B.

If  $F_m \gg F_0$ , the wave field is highly nonlinear: No linear spatial derivatives are present in the governing equation in the continuum limit (14). The wave field consists of combinations of compact solitary waves, whose wavelength is constant (approximately five sphere diameters) and whose phase velocity depends on their amplitude (14, 15). Short input signals lead to a single solitary wave; longer inputs lead to a train of solitary waves or shock-like structures (see insets in Fig. 1A) (14, 21, 22). Solitary waves travel with a phase velocity  $V_s$  that depends on the maximum dynamic force  $F_m$  and the static precompression force  $F_0$  (14, 18, 23). The frequency content of the wave field is proportional to  $k_s V_s$ , with a wavenumber  $k_s$  that depends on properties of the power-law material (14). The frequency content can be controlled by controlling  $V_s$  through  $F_0$ . Here we use chains of spheres as a simple representation of a nonlinear medium with constitutive-law exponent  $n = 3/2$  (14, 15, 24).

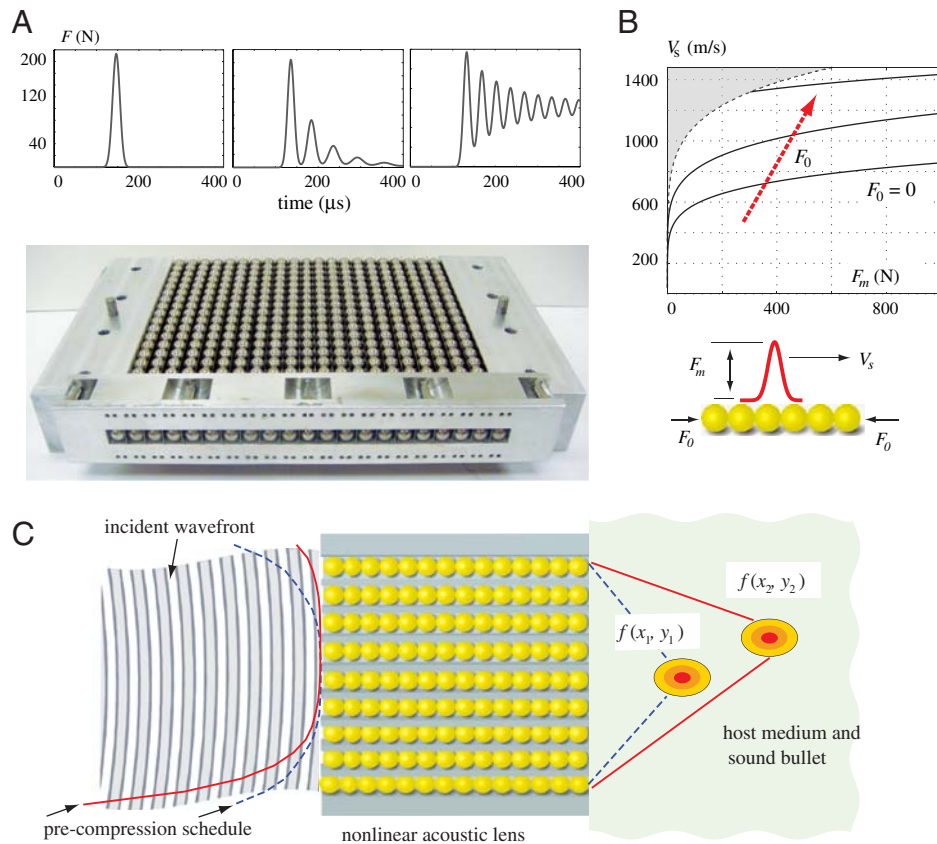
We designed a nonlinear acoustic lens by assembling chains of spheres into an array. The individual chains in the array were precompressed differentially such that an acoustic signal with fixed phase incident on the lens results in transmitted waves with phase delays. The precompression and phase delays were chosen so that the individual waves transmitted by each chain coalesce at a focal point in the adjacent host medium (Fig. 1C). For an impulsive input to the lens, Fig. 2 illustrates the phase delays (Fig. 2A), transmitted waves shortly after their generation (Fig. 2B), and the focusing of the acoustic energy in the host medium, with a symmetric pressure distribution with one maximum and one minimum (Fig. 2C). These are obtained from analytical calculations with air as the host medium (see equations in *SI Text*). The acoustic energy in the host medium is focused into a “sound bullet”—a traveling, compact region of high energy density. Sound bullets result from the coalescence of acoustic waves, which have

Author contributions: C.D. designed research; A.S. performed research; A.S. and C.D. analyzed data; and A.S. and C.D. wrote the paper.

The authors declare no conflict of interest.

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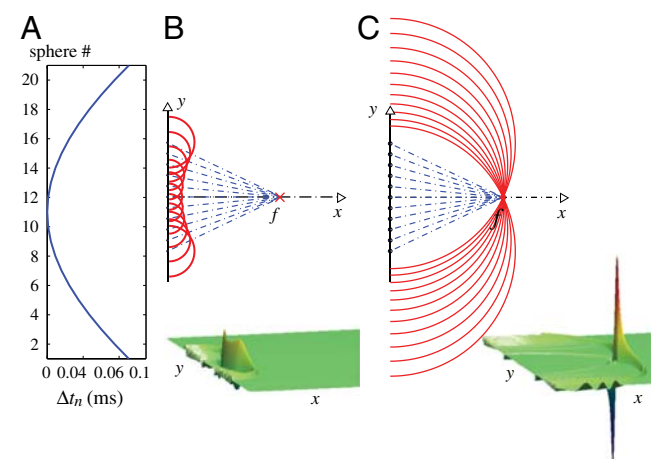
**Fig. 1.** Nonlinear acoustic lens. (A) Prototype consisting of 21 independent chains, each composed of 21 steel spheres and employed as the wave-modulation component (density  $\rho = 8100 \text{ Kg/m}^3$ , Young's modulus  $E = 195.6 \text{ GPa}$ , and diameter  $D = 9.5 \text{ mm}$ ). Numerical simulation of the prototype shows it to be capable of supporting single solitary waves (Upper Left Inset), trains of solitary waves (Upper Center Inset), and shocks (Upper Right Inset). (B) The phase velocity  $V_s$  of waves with force amplitude  $F_m$  traveling in the acoustic lens strongly depends on the initial strain state determined by static precompression force  $F_0$ . The gray shaded region of the parameter space indicates where the response is weakly nonlinear. (C) Because the phase velocity depends on  $F_0$ , the distribution of  $F_0$  may be chosen to focus acoustic energy into a sound bullet. The position of the focus lies on the len's symmetry axis  $f(x_f, y_f)$  when  $F_0$  is symmetric about it (dashed blue line) or off the symmetry axis  $f(x_2, y_2)$  when  $F_0$  is asymmetric (solid red line).

frequencies in the audible range for the lens parameters we chose. The individual waves transmitted by the nonlinear acoustic lens are compact. They consist of a single wave crest for an input

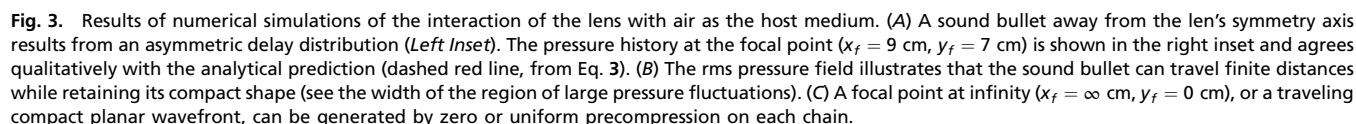
of short duration. This characteristic of the transmitted waves leads to the compact nature and accurate focusing of sound bullets. In contrast to optical bullets that are theorized to reside in optically dispersive media (25, 26), sound bullets arise when solitary waves created within a nonlinear granular medium coalesce in a linear nondispersive medium. This makes sound bullets feasible in a variety of host media.

The analytical calculations on which Fig. 2 is based assume perfectly circular wave fronts radiating from an idealized interface between the lens and the host medium. To test to what extent the analytical results carry over to a more realistic setting, we use numerical simulations with a fluid-structure-interaction (FSI), finite-element (FE) model coupled to a discrete-particle (DP) model (see *SI Text*). The simulated acoustic lens is identical to the prototype illustrated in Fig. 14, with an incident pulse generated by impact with a conformal striker. For a striker with an impact velocity of  $1 \text{ ms}^{-1}$  and a mass equal to that of 21 spheres, the resulting pressure field in air for a focal point ( $x_f = 9 \text{ cm}$ ,  $y_f = 7 \text{ cm}$ ) is shown in Fig. 3A, along with the required time delay. The sound bullet, formed off axis because of the selected asymmetric precompression schedule, attains a maximum pressure  $p_B \approx 79 \text{ Pa}$ , corresponding to  $38 \text{ dB}$  [ $\text{dB} = 20 \log_{10}(p/p_0)$ , with a reference pressure  $p_0 = 1 \text{ Pa}$  (27)]. The pressure distribution at the focal point agrees qualitatively with that predicted analytically (see Eq. 3 in *Materials and Methods*) in that both the wavelength and double-peaked shape agree (inset in Fig. 3A).

Because the sound bullet is a superposition of compact waves, it propagates in the vicinity of the focal point at the speed of sound of the host medium, as long as the individual compact

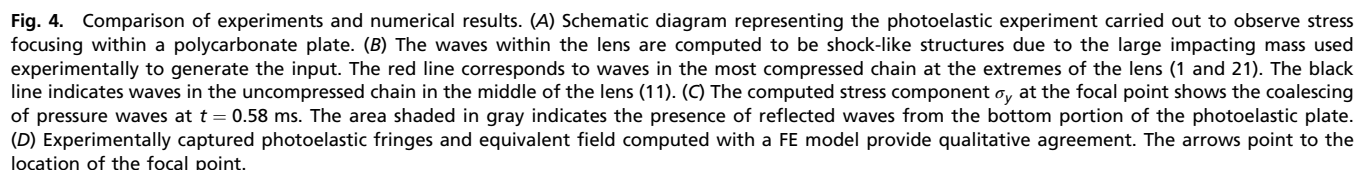


**Fig. 2.** Results of analytical calculations in support of the lens design. (A) Time delay distribution (see equation in *SI Text*) necessary to obtain a focal point in air at ( $x_f = 13 \text{ cm}$ ,  $y_f = 0 \text{ cm}$ ), along the len's symmetry axis. (B) Schematic of the wave field shortly after generation (Upper, lines of constant phase in red and ray paths in blue), and analytical solution for pressure field (Lower, from Eq. 3). (C) Wave field and analytical solution for pressure at a later time, when the acoustic energy coalesces at the focal point. The resulting sound bullet is composed of a symmetric pressure maximum and minimum.



The generation of stable and compact solitary waveforms seen in these results arises because nonlinearity and dispersion balance in the lens (14, 15). The stability and compactness are retained even if the input amplitude is increased, making it possible to produce arbitrarily large signals within the lens as long as the force-deformation power law is unaltered. As a consequence, the pressure amplitude of sound bullets generated with our lens increases as the impact velocity  $v_0$  increases. For example, with

To corroborate our analytical and numerical results, we performed experiments to demonstrate the focusing of pressure waves in a solid host medium (a polycarbonate plate) (Fig. 4A). To compare with the experimental results, we extended the analytical calculations and the numerical DP/FE simulations to account for stresses and strains in solids (see *SI Text*). The DP/FE model suggests that the large striker mass (longer contact duration) used in the experiments leads to shock-like waves propagating within the lens (Fig. 4B), in place of the single solitary wave generated with a small striker mass (shorter contact duration) (Fig. 1A). We chose the precompression (see figures in *SI Text*) to obtain a focal point in the polycarbonate plate 10 cm from the lens's edge on its symmetry axis (Fig. 4A), and





we visualized the focused waves in the experiments by measuring photoelastic fringes in the polycarbonate plate. The photoelastic fringes produced by the dynamic stress in the plate were captured with a black-and-white high-speed camera and compared to the DP/FE model. Numerical simulations indicated that the stress along the symmetry axis at the focal point has a shock-like profile (Fig. 4C), and this was used to guide the image acquisition system. The numerically simulated photoelastic stress fringes agree qualitatively with those obtained experimentally (Fig. 4D). Subtle misalignment of the striker, spheres, and midplane of the plate produced other wave modes that affect the experimentally measured photoelastic fringes. Nonetheless, a clear stress concentration is observed, reaching the focal point only  $\approx 5\%$  later in the experiments than in the numerical simulation (Fig. 4D).

The nonlinear acoustic lens provides a more compact focal region than is achievable with an array of linear sources, especially when operating in the transient regime (e.g., generating single sound bullets). These improvements stem from the nonoscillatory and compact nature of signals transmitted by our lens (see Eq. 1 in *Materials and Methods*), which is not achievable with traditional linear devices. It is possible that our lens design may be further improved by employing nonlinear media with a higher constitutive-law exponent  $n$ , as the wavelength of solitary waves scales as  $\lambda = \pi a [\sqrt{n(n+1)/6}]/(n-1)$  (14) with  $a$  as the particle size, so that greater  $n$  may lead to a sharper focus.

The nonlinear lens expands the capabilities of existing acoustic transducers. The chains of particles composing the lens transform a given incident acoustic signal into either a single pulse or trains of pulses (compact solitary waves), which are tunable by mechanical means. The phase velocity of the waves within the lens can be controlled by adjusting the static precompression of each chain, whereas the wavelength is determined by the size of the particles. These characteristics allow the focusing of waves transmitted into a solid or fluid host medium and the generation of compact sound bullets of very large amplitudes (here we demonstrated up to 57 dB amplification at the focus). Sound bullets can travel finite distances in the host medium while retaining their compact shape. Such compact, transient pressure pulses were not achievable with previously available technologies, which only allow oscillatory signals. The acoustic lens can also be used as an effective filter, capable of controlling the frequency content of the pressure field in the focal region by controlling the precompression. Acoustic lenses like the one we demonstrated have the potential to dramatically impact a variety of applications, such as biomedical devices, nondestructive evaluation, and defense systems. For example, sound bullets may conceivably be used as a noninvasive scalpel to accurately target tumors in hyperthermia applications.

## Materials and Methods

**Analytical Model.** In the continuum limit (long wavelength compared to the sphere diameter), the solitary waves are thought to have the compact structure (see ref. 14)

$$u_n(t) = \begin{cases} A_n \cos^4 \alpha_n & \alpha_n \in [-\pi/2, \pi/2], \\ 0 & \text{otherwise,} \end{cases} \quad [1]$$

with argument

$$\alpha_n = k_s [x - V_{s,n}(t - \Delta t_n)]. \quad [2]$$

Here,  $u$  is the displacement of a material point, and  $x$  and  $t$  are the spatial and temporal coordinates. For a given particle size, the wavenumber  $k_s$  is a constant, i.e.,  $k_s = \sqrt{10}/(5D)$  (14). The index  $n$  indicates a particular chain of spheres within the lens.

In our theoretical analysis, we consider the focusing properties of the nonlinear acoustic lens in solid and fluid host media, limiting the study to the case  $F_m \gg F_0$ . The interactions between the individual granular chains and the host medium are assumed to be contact interactions of solid spheres

with either a solid half space or thin metal plates separating the spheres themselves from a fluid half space. In both cases, we assume the mechanical disturbances to be perceived as point sources by the linear isotropic host medium. Geometric or ray acoustics (20) can then be used to estimate the phase delay distribution  $\Delta t_n$  necessary to focus energy at a desired location  $(x_f, y_f)$  (see equations in the *SI Text*).

In the case of a fluid host medium, assuming that the displacement of each thin metal plate is represented by the same function as that describing a solitary wave (Eq. 1) with amplitude  $A_n$ , yields the pressure field (see equations in the *SI Text*)

$$p(x, y, t) = \frac{\rho c k_s a}{2} \sum_{n=1}^N \frac{A_n V_{s,n} [2 \sin(2k_s \phi_n) + \sin(4k_s \phi_n)]}{r_n}. \quad [3]$$

This pressure field is nonzero only where  $k_s \phi_n \in [-\pi/2, \pi/2]$ ; it is zero otherwise. Here  $\rho$  is the density of the host medium,  $c$  is the linear speed of sound in the host medium, and the factor  $a$  is a small coordinate shift to avoid singularities in the linear solution at the lens-host medium interface. Because the pressure amplitude cannot easily be obtained analytically, we fix  $aA_n = \text{constant}$  in Eq. 3 to match numerical simulations. In Eq. 3,  $N$  is the number of chains composing the lens,  $r_n = \sqrt{(x - x_n)^2 + (y - y_n)^2}$ , and  $\phi_n = V_{s,n}(r_n/c - a/c - t + \Delta t_n)$ .

**Numerical Model.** The FSI model is employed to evaluate the interaction of moving thin metal plates and the fluid host medium. Both air and the particles in the lens are assumed initially at rest, and, for simplicity, the pressure at the boundaries is assumed zero (corresponding to assuming the fluid to be confined to a closed box); this explains the reverberation seen in Fig. 3A. The DP model treats each sphere as a point mass, and the contact between any two spheres is represented as a spring of stiffness determined by Hertz contact theory (14–18, 24).

**Experimental Methods.** The experimental prototype of the acoustic lens (Fig. 1A) is made of aluminum 6061-T051 and measures  $30.5 \times 23 \times 7.6$  cm. It accommodates 21 chains each composed of 21 stainless steel spheres (see properties listed in the table in *SI Text*). Each chain was independently statically precompressed by a different force  $F_0$ , and the chains were separated from each other with stainless steel shim stock of thickness 0.15 mm. The inside surfaces of the lens casing were lined with Teflon sheets to minimize friction. The front and back sides of the lens casing feature slots (see figure in *SI Text*) to accommodate individual strands of fishing line used to precompress each chain. The topmost sphere of each chain was threaded with fishing line and was secured to one side of the lens casing, to which weights were connected. Water bottles with variable water content were used to provide the necessary resolution in setting the precompression weights (see figure in *SI Text* for the required time delay and associated precompression forces). The assembled lens was set vertically on a polycarbonate plate (see table in *SI Text*) of dimension  $25 \times 25 \times 1.9$  cm, which in turn rested on a table (see figure in *SI Text*).

Upon applying the differential precompression, the lengths of the chains differed, posing a challenge in imparting mechanical energy to all chains simultaneously. The adopted solution consisted of drilling holes in the first sphere of each chain to accommodate a 2.5-cm-long screw. The impacting plate was modified by adding 21 holes (2.5 cm in depth, 1 cm in diameter) to accommodate the screws protruding from each sphere. The holes were then filled with a two-part CASTAMOUNT acrylic resin from Pace Technologies. In this manner, the contact edge of the striker plate aligned with the top portion of each chain (see figure in *SI Text*). Finally, the camera was triggered using a PCB Piezotronics, Inc. accelerometer placed on the top portion of the striker assembly.

With the DP/FE model as guidance, a Vision Research, Phantom V12 high-speed camera was triggered 280  $\mu$ s after impact. The black-and-white camera was set to acquire images at 300,000 samples per second, plus a reference image ( $25 \times 10$  cm) of the polycarbonate plate at rest (see figure in *SI Text*). To remove the shadows of the fishing line and to enhance the visible photoelastic fringes, the reference image was subtracted from each acquired frame.

**ACKNOWLEDGMENTS.** The authors thank Vitali F. Nesterenko for initial discussions, Tapio Schneider for helpful suggestions, and Veronica Eliasson for valuable experimental insight. Funding from the Army Research Office (Grant 54272-EG) and National Science Foundation (Materials Research Science and Engineering Center at the California Institute of Technology and NSF-CMMI-0806762-CAREER) is also acknowledged.

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